# Heavy Ion Collisions at RHIC and at the LHC: Physics Challenges

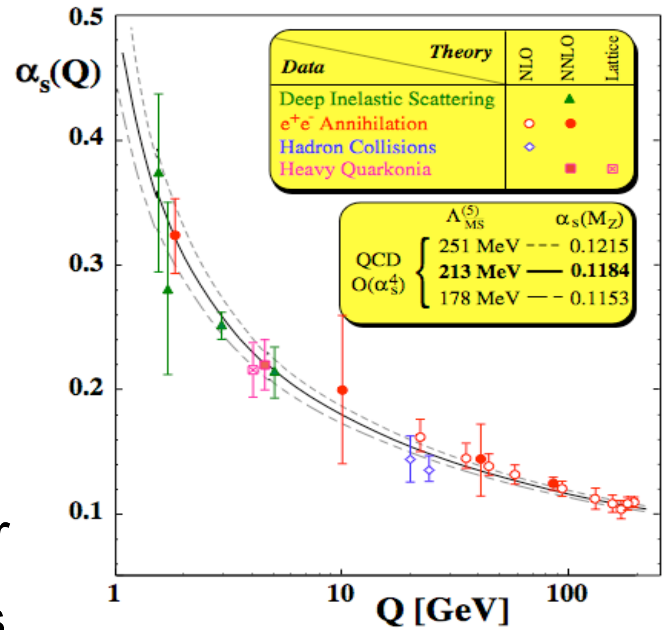
Urs Achim Wiedemann
CERN TH and SUNY Stony Brook


# From elementary interactions to collective Phenomena

1973: asymptotic freedom

QCD = quark model +gauge invariance

$$q(x) \rightarrow \exp\left(i\omega_a(x)T^a\right)\; q(x), \qquad [T^a, T^b] = i f^{abc} T_c$$




Today: mature theory with a precision frontier

- background in search for new physics
- TH laboratory for non-abelian gauge theories

How do collective phenomena and macroscopic properties of matter emerge from fundamental interactions ?

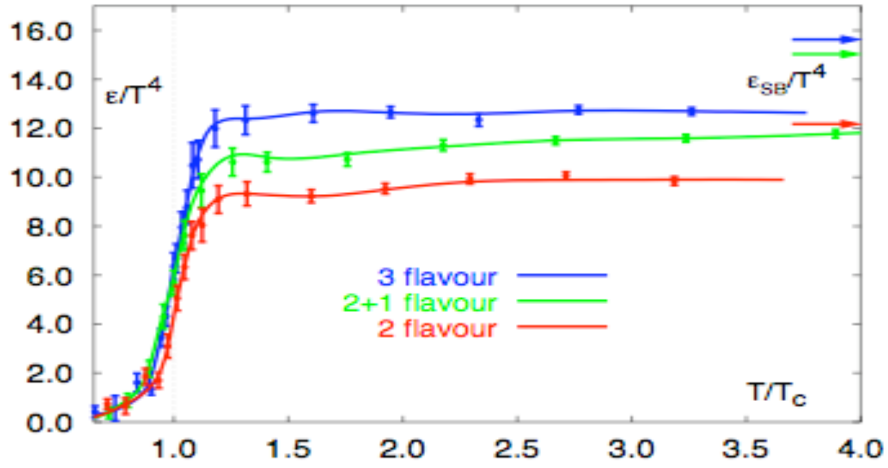
QCD much richer than QED:

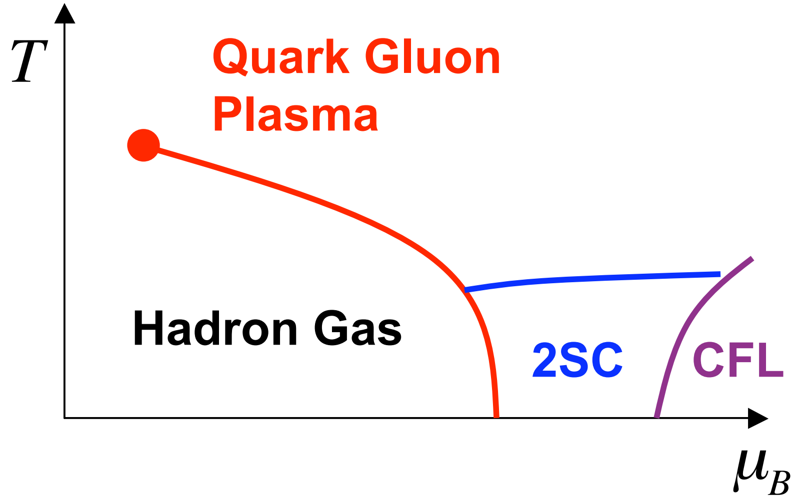
- non-abelian theory
- degrees of freedom change with

# Open questions

- What is the QCD equation of state? How can we test it?

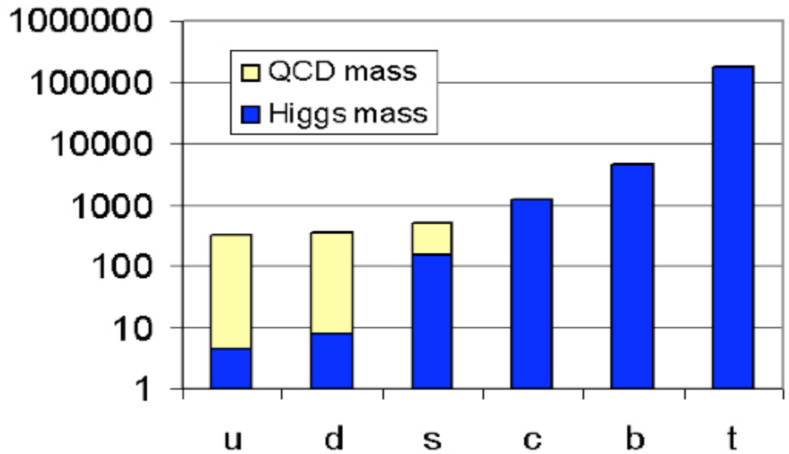
$$T_c \approx 175\ MeV \quad \varepsilon_c \approx (3-5)\ \varepsilon^{cold}_{nuclear\ matter}$$




- What is the origin of mass in the universe?

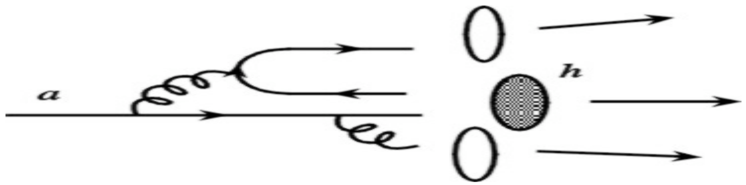
$$\langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \approx (250\ MeV)^3$$



# … and more questions…

- What are the properties of matter at the highest temperatures and densities?
  - Degrees of freedom?
  - Viscosity?
  - Heat Conductivity?
  - Transport of conserved quantum numbers?
- What are the dominant microscopic mechanisms of QCD non-equilibrium dynamics and thermalization?
  - Parton energy loss?
  - Plasma Instabilities, color chaos?
- Confinement: How does hadronization proceed dynamically?

  How is it changed in dense QCD matter?




- Why is there no strong CP violation? Or is there at finite temperature?

$$L_{QCD}^{\not{CP}} \propto \theta \; tr\left[G^{\mu\nu}\tilde{G}_{\mu\nu}\right] \qquad \theta \approx 0$$

… and many more …

# … and more specific questions …

(From the NSAC 2002 Long Range Plan)

1) In relativistic heavy-ion collisions, how do the created systems evolve ? UI
   Does the matter approach thermal equilibrium ? Y
   What are the initial temperatures achieved ? UI

2) Can signatures of the deconfinement phase transition be located as the hot matter produced in relativistic heavy-ion collisions cools ? UI-TBD

3) What are the properties of the QCD vacuum and what are its connections to the masses of the hadrons ? TBD
   What is the origin of chiral symmetry breaking ? TBD

4) What are the properties of matter at the highest energy densities ? UI
   Is the basic idea that such matter is best described using fundamental quarks and gluons correct ? UI

Y = Yes, UI=Under Investigation, TBD=To Be Determined

<u>Question:</u>

Why do we need collider energies

$$\sqrt{s_{NN}} = 200\, GeV \quad [RHIC]$$

$$\sqrt{s_{NN}} = 5500\, GeV \quad [LHC]$$

to test properties of dense QCD matter
which arise on typical scales

$$T \approx 150\, MeV, \quad Q_s \approx 1-2\, GeV \text{ ?}$$

# Answer 1: Large quantitative gains

Increasing the center of mass energy implies

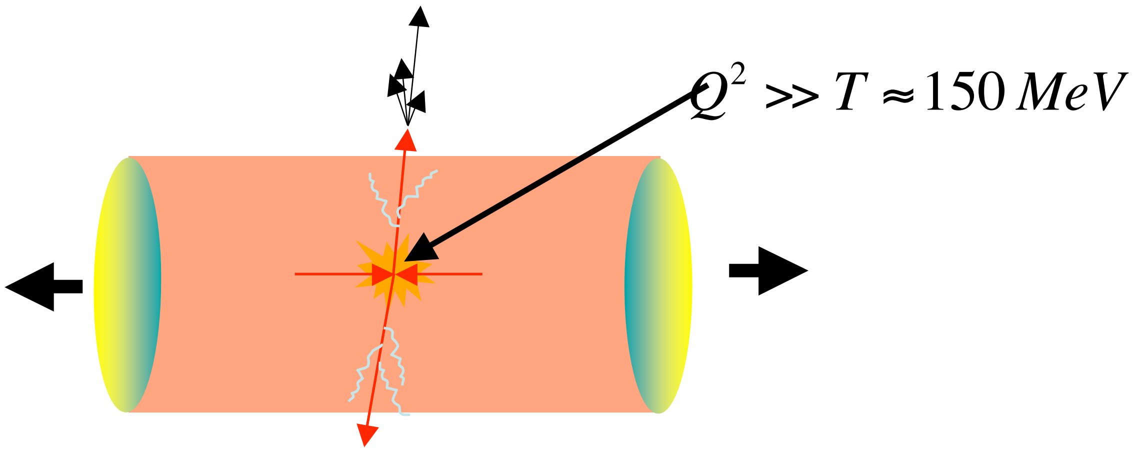
- ⇨ Denser initial system, higher initial temperature
- ⇨ Longer lifetime
- ⇨ Bigger spatial extension
- ⇨ Stronger collective phenomena

A large body of experimental data from RHIC supports this argument (see talk of Jamie Nagle).

# Answer 2: Qualitatively novel access to properties of dense matter

For a detailed experimentation with dense QCD matter, one ideally wants to do DIS on the QGP.

… and we can by using auto-generated probes at high $\sqrt{s_{NN}}$




Large $\sqrt{s_{NN}}$ allows us to embed well-controlled large-$Q^2$ processes (hard probes) in dense nuclear matter.

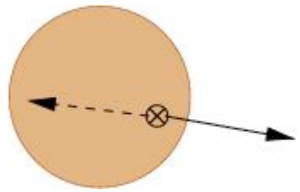
Q: How sensitive are hard probes?

# Bjorken's original estimate and its correction

Bjorken 1982: consider jet in p+p collision, hard parton interacts with underlying event ⇒ collisional energy loss

$$dE_{coll}/dL \approx 10\,GeV/fm$$

Bjorken conjectured monojet phenomenon in proton-proton



Today we know (th): radiative energy loss dominates

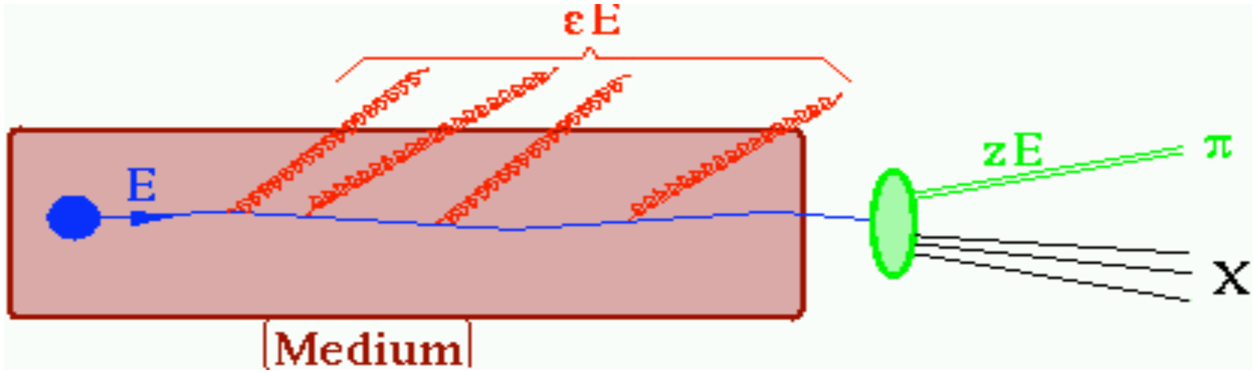
$$\Delta E_{rad} \approx \alpha_s \hat{q} L^2$$

Baier Dokshitzer Mueller Peigne Schiff 1995

- p+p: $L \approx 0.5\ fm, \quad \Delta E_{rad} \approx 100\ MeV$ Negligible !
- A+A: $L \approx 5\ fm, \quad \Delta E_{rad} \approx 10\,GeV$ Monojet phenomenon!

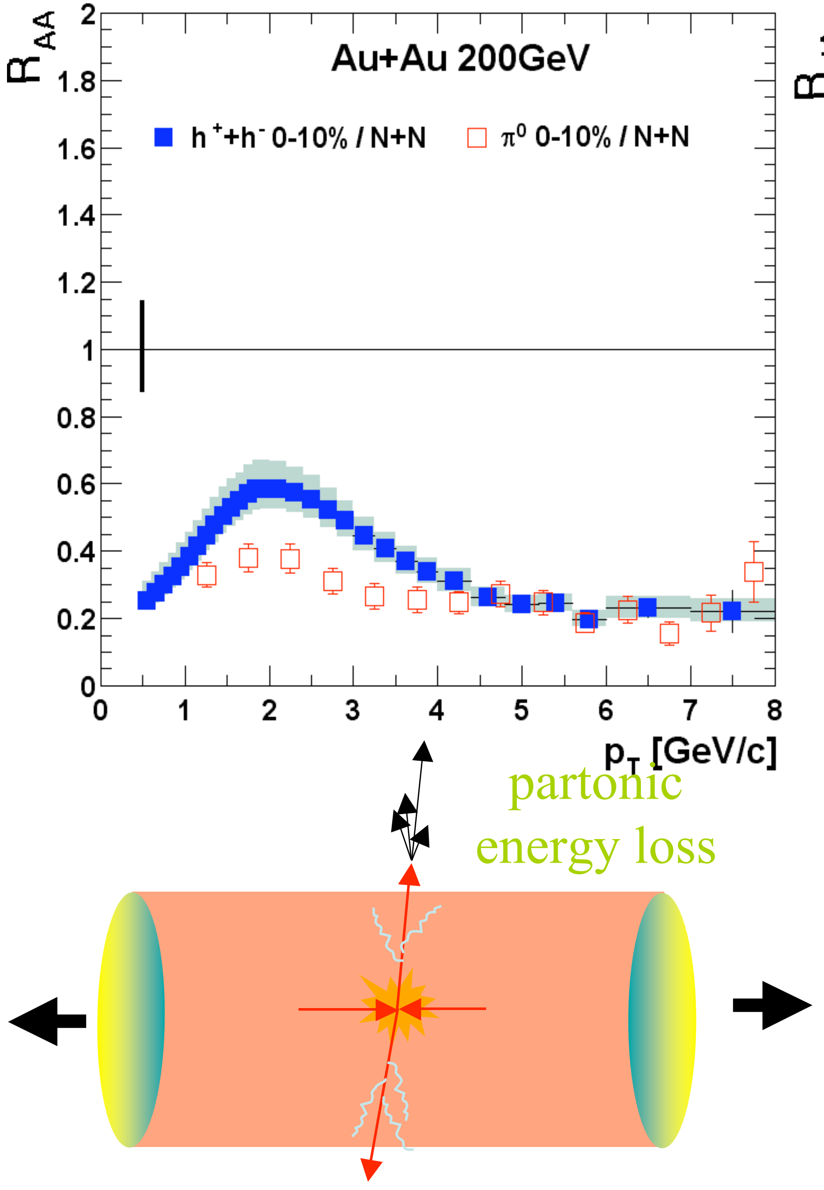
observed at RHIC, see talk by Jamie Nagle

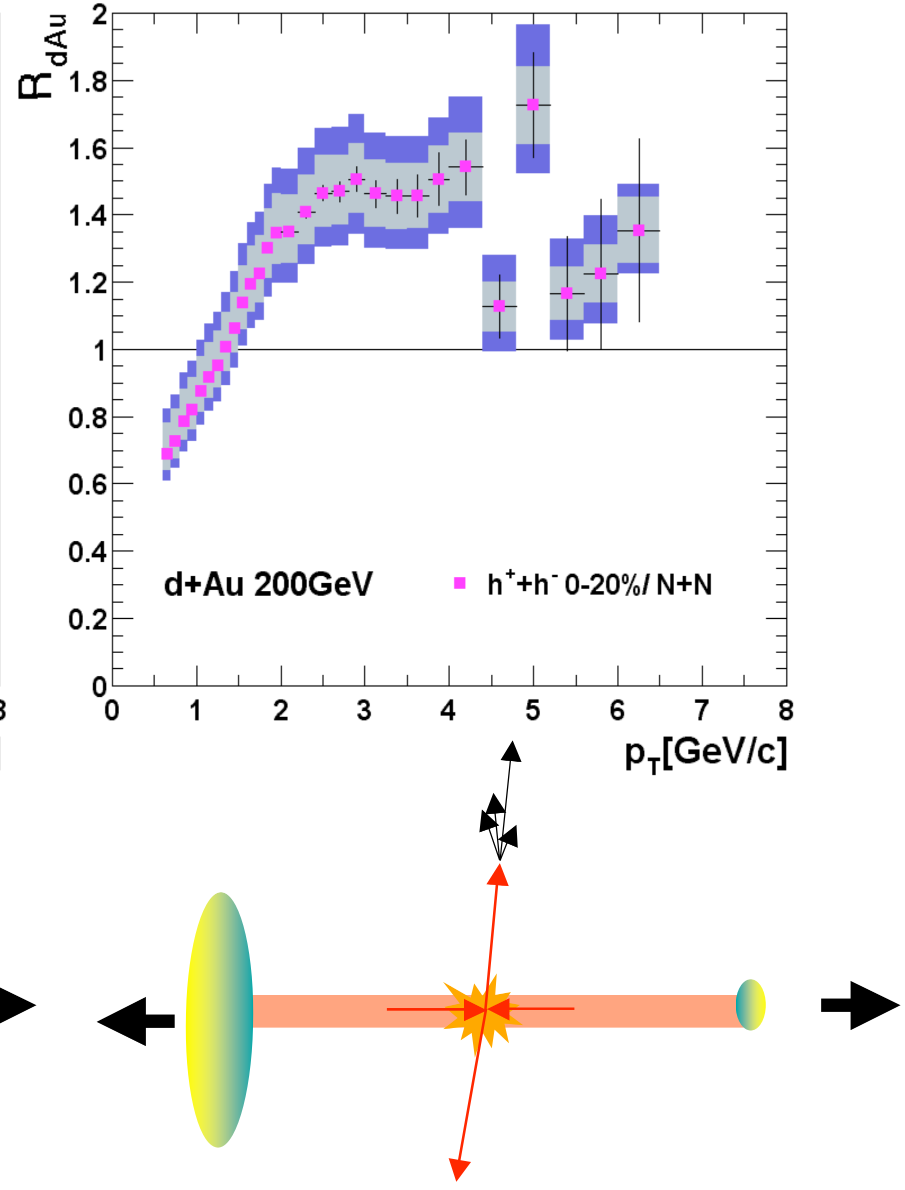
# High $p_T$ Hadron Spectra



# Centrality dependence: Au+Au vs. d+Au

- Final state suppression
- Initial state enhancement



# Leading hadron suppression at RHIC:

Abundant yield at collider energies

(detailed differential study of experimental signal possible)

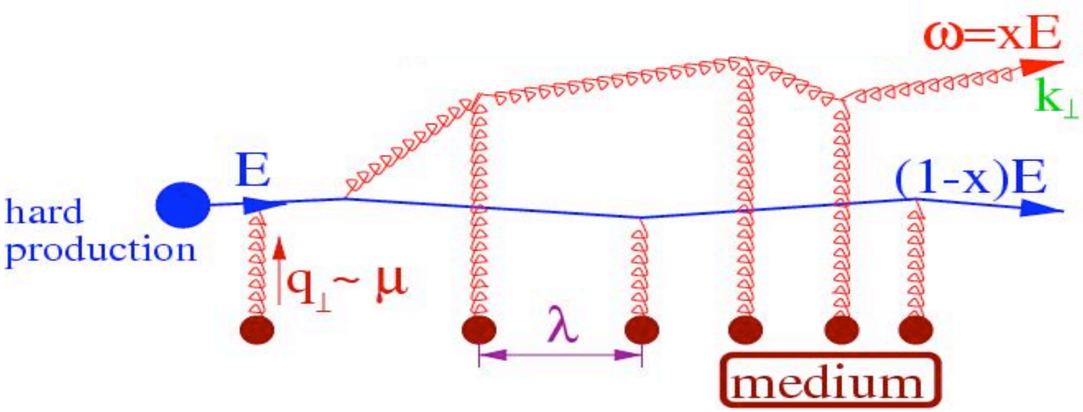
+ robust and large signal

(medium effect much larger than theoretical uncertainties)

= Basis for controlled experimentation
and controlled theoretical interpretation

# The medium-modified Final State Parton Shower

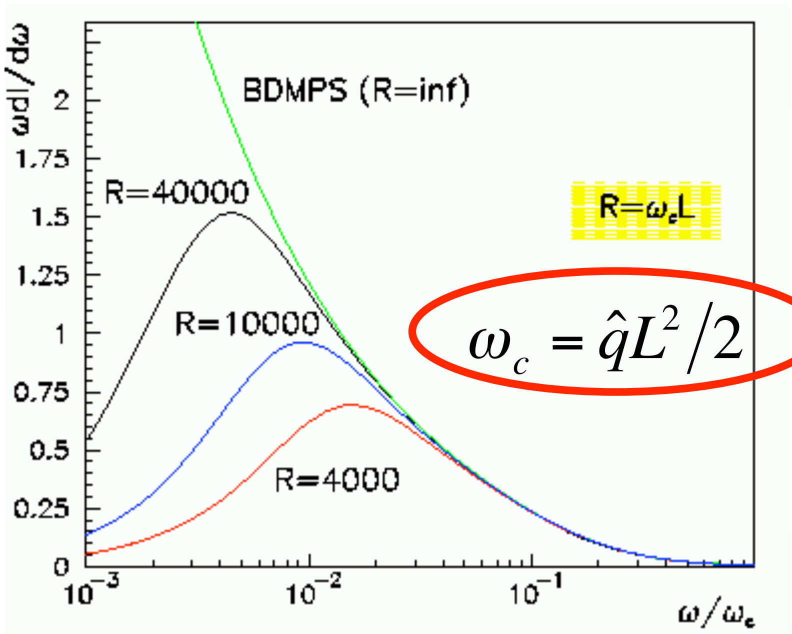
Baier, Dokshitzer, Mueller, Peigne, Schiff (1996); Zakharov (1997); Wiedemann (2000); Gyulassy, Levai, Vitev (2000); Wang ...

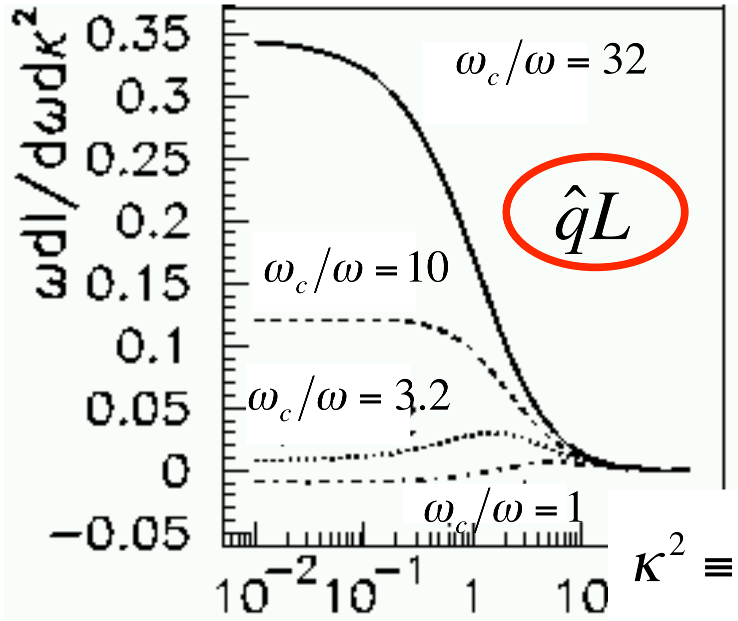



Medium characterized by transport coefficient:

$$\hat{q} \equiv \frac{\mu^2}{\lambda} \propto n_{density}$$

- energy loss of leading parton
- pt-broadening of shower




$$\kappa^2 \equiv \frac{k_T^2}{\hat{q}L}$$

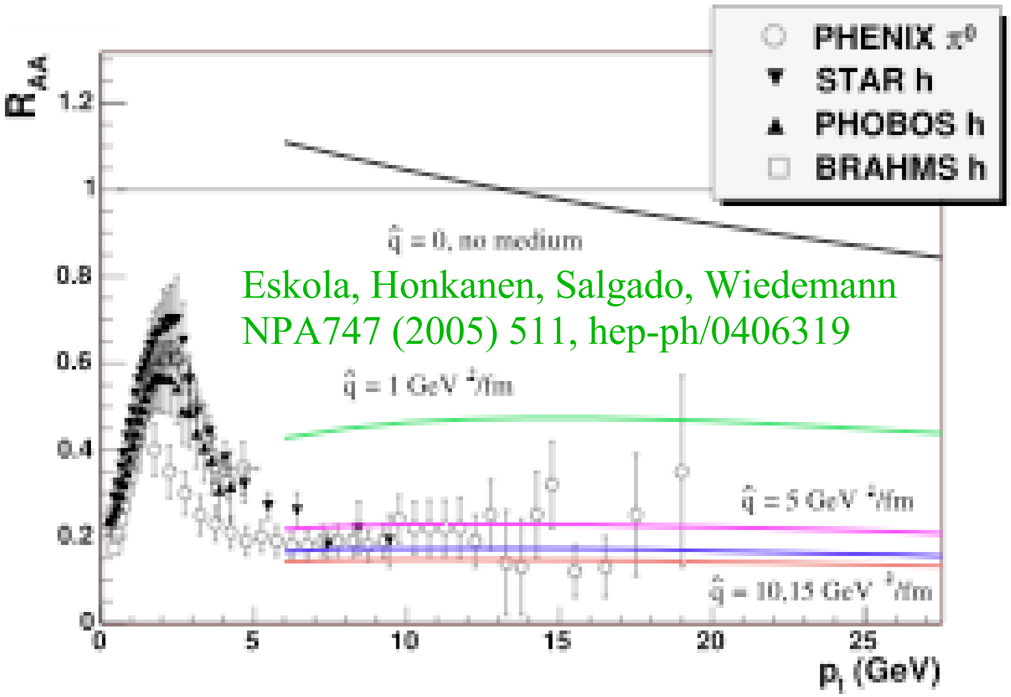
Salgado,Wiedemann PRD68:014008 (2003)

# The fragility of leading hadrons

• Why is $R_{AA} \sim p_T$-independent?

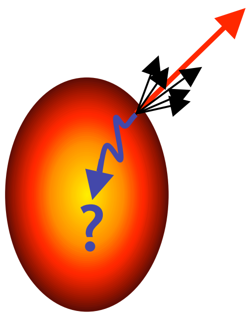
Trigger bias more severe for large $p_T$

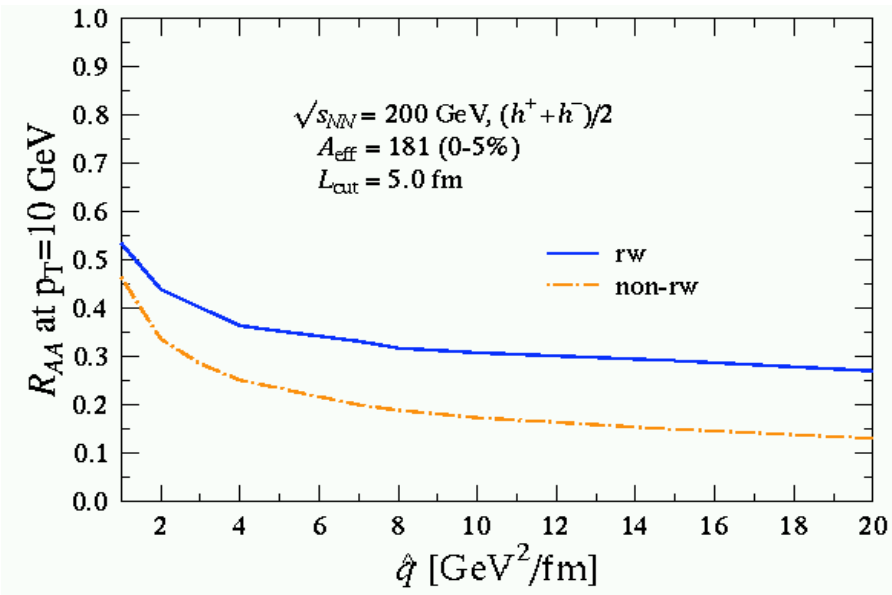
$$\sigma \propto \int dz \frac{z^{n(p_T)-1}}{p_{T,hadr}^{n(p_T)}} D_{h/q}^{frag}(z,Q^2)$$



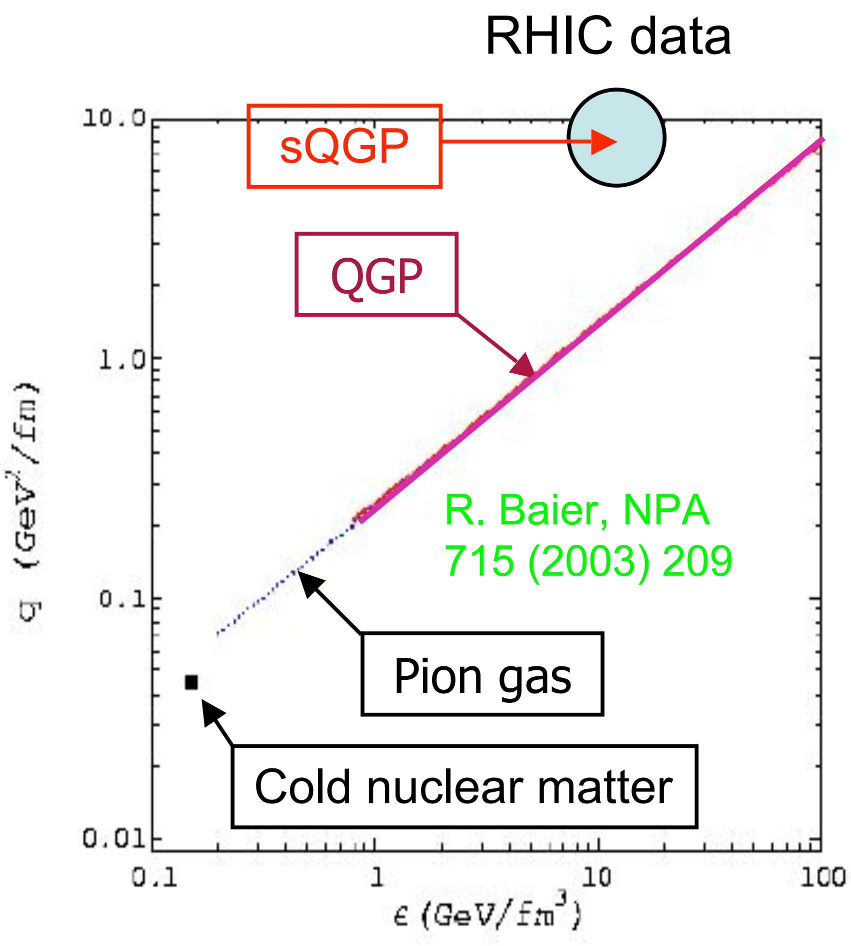

• Why is $R_{AA}$ = 0.2 natural ?

Surface emission limits sensitivity to $\hat{q}$



# The produced matter is opaque - why?




- $\hat{q}$ traces energy density

$$\boxed{\hat{q}(\tau) = c\,\varepsilon^{3/4}(\tau) \quad \Leftarrow c_{ideal}^{QGP} \approx 2}$$

$$\boxed{c > 5\, c_{ideal}^{QGP}}$$

**"Opacity problem"**

WHY?

- Interactions in produced matter much stronger than in ideal QGP.
- $\hat{q}$ measures combination of energy density and flow (some support from RHIC data)
- parton energy loss calculations need quantitative improvements (no indication from RHIC that this is dominant effect)

# How can we relate $\hat{q}$ to fundamental properties of matter?

- $\hat{q}$ defines short-distance behavior of expectation value of two light-like Wilson lines

$$N(x,y) \equiv 1 - \left\langle Tr\left[W^{A+}(x)W^{A}(y)\right]\right\rangle \approx \hat{q}L(x-y)^2$$

o Related to operators, which measure color field and which may be calculable in lattice QCD.

o Can this be calculated with other modern methods (AdS/CFT) ?

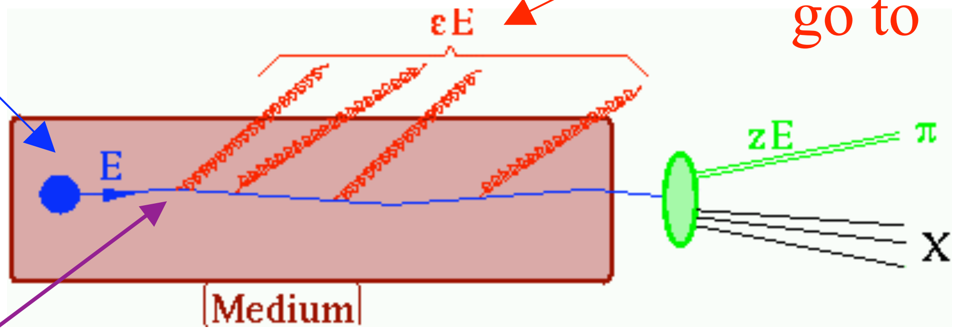
o Even if $\hat{q}$ is not calculable from 1st principles, its energy dependence is, since it satisfies non-linear QCD evolution equation.

Well-defined but difficult problem in QCD

# How can we better gauge ‘hard probes’?

How does this parton thermalize ?

Where does this associated radiation go to ?




What is the dependence on parton identity ?

$$\Delta E_{gluon} > \Delta E_{quark,m=0} > \Delta E_{quark,m>0}$$

- Numerous independent tests possible

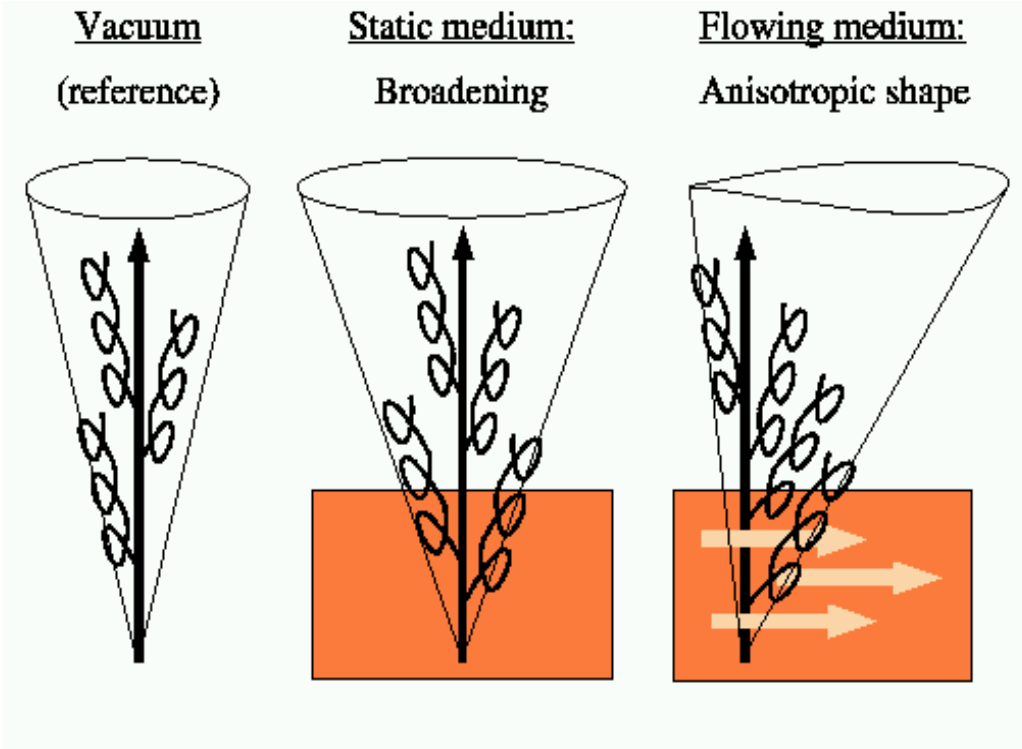
  ⇨ Basis for controlled experimentation with dense matter.

- Tremendous theoretical and experimental activity to further test the microscopic dynamics underlying high-pt hadron suppression.

# Jets in pionic winds and partonic storms

If medium shows strong collective flow, what are additional measurable consequences?

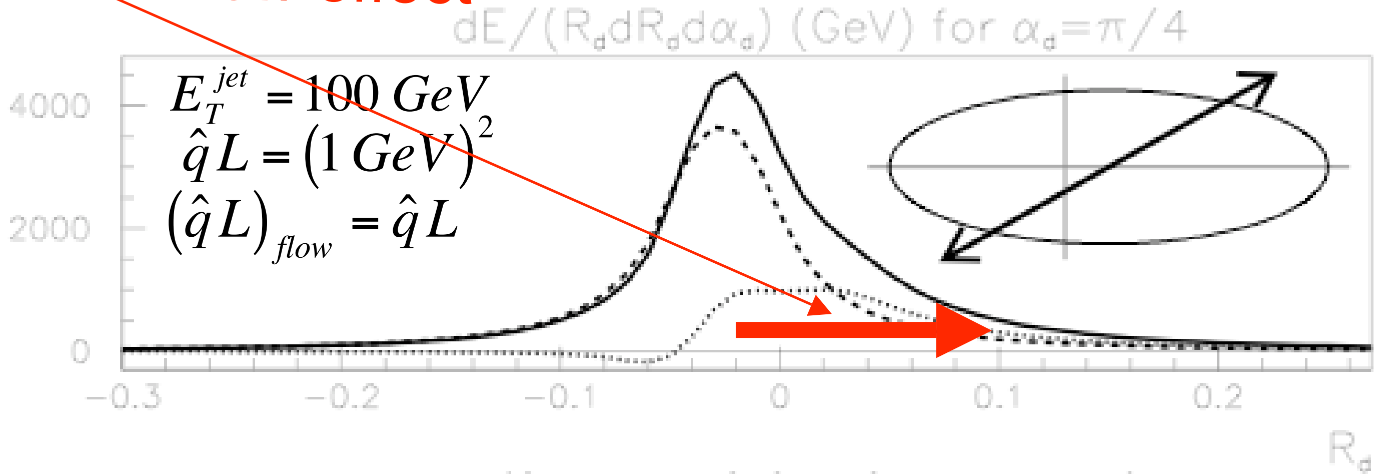
Armesto, Salgado, Wiedemann, Phys. Rev. Lett. 93 (2004) 242301



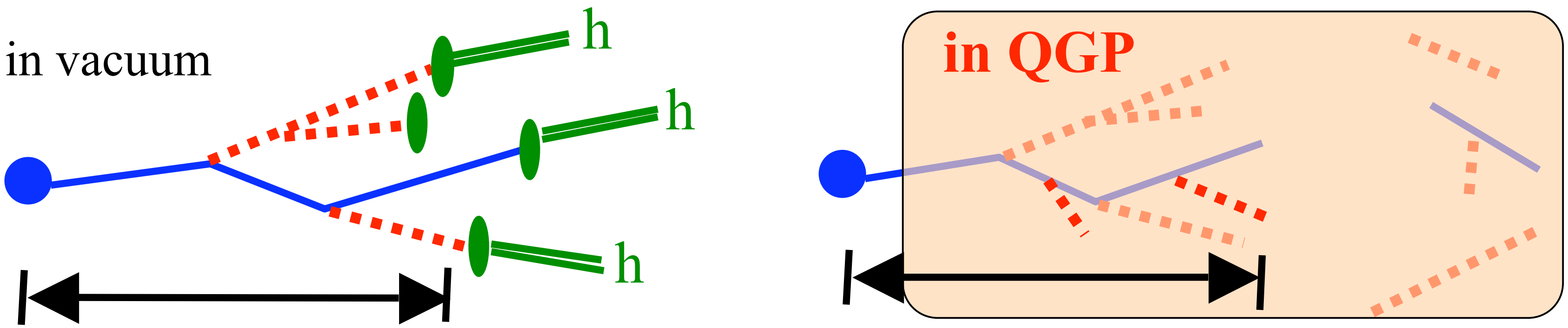

Hard partons are not produced in the rest frame comoving with the medium

$$T^{\mu\nu} = (\varepsilon + p)\, u^{\mu} u^{\nu} - p\, g^{\mu\nu}$$

Flow effect

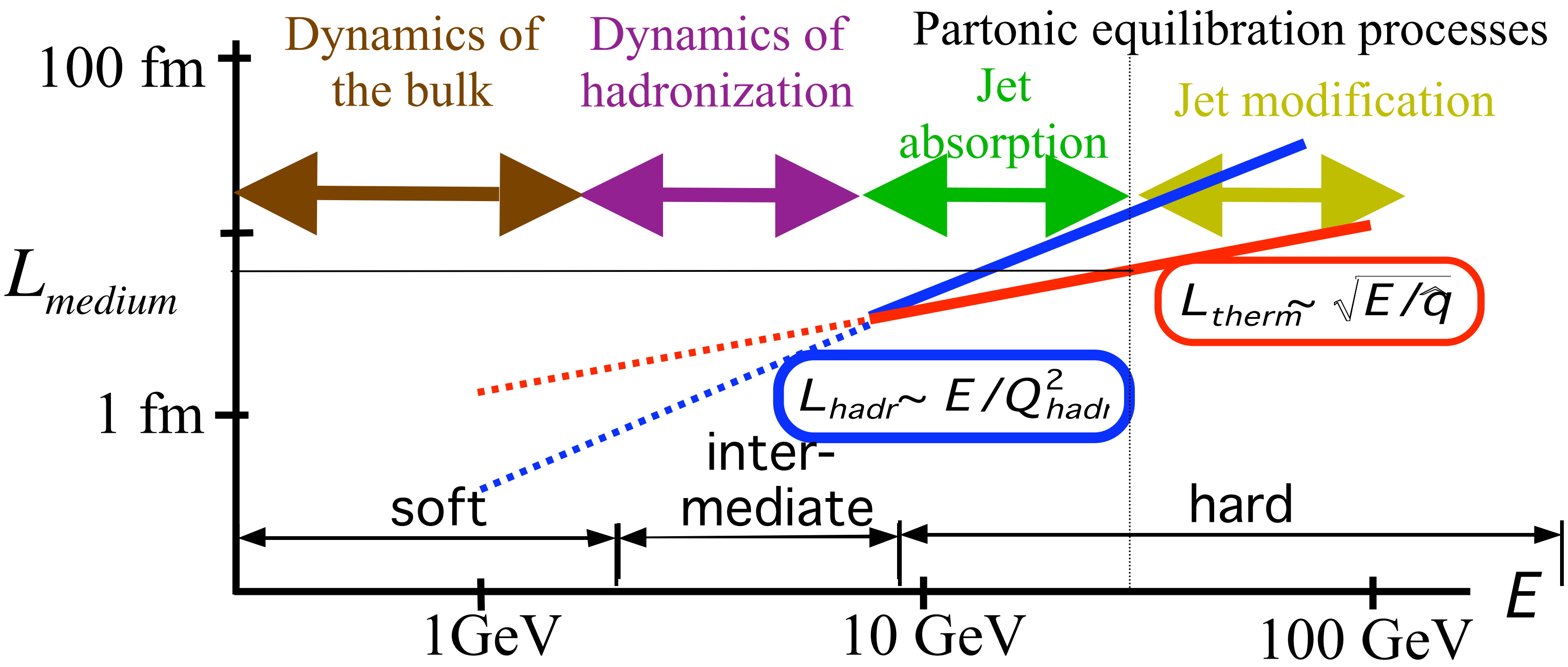


# Times scales: hadronization vs.thermalization



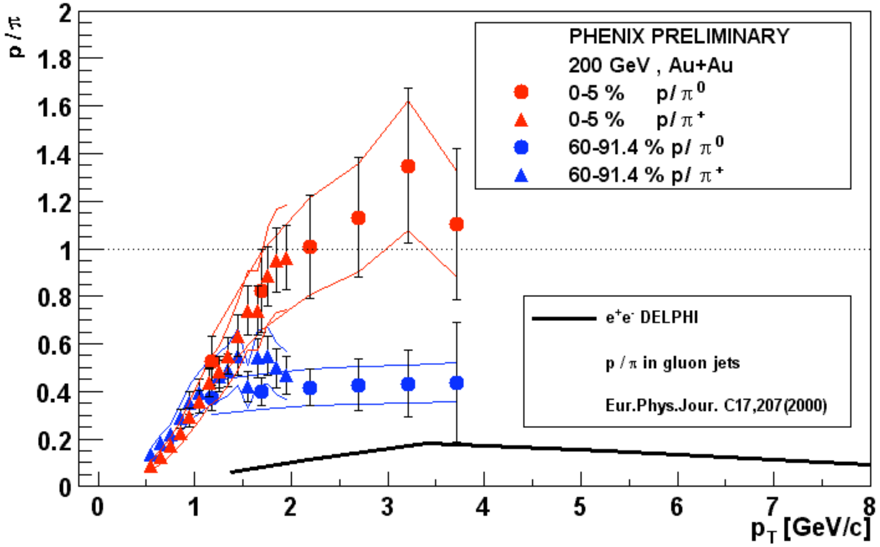

$$L_{hadr} = const\,\frac{E}{Q^2}$$

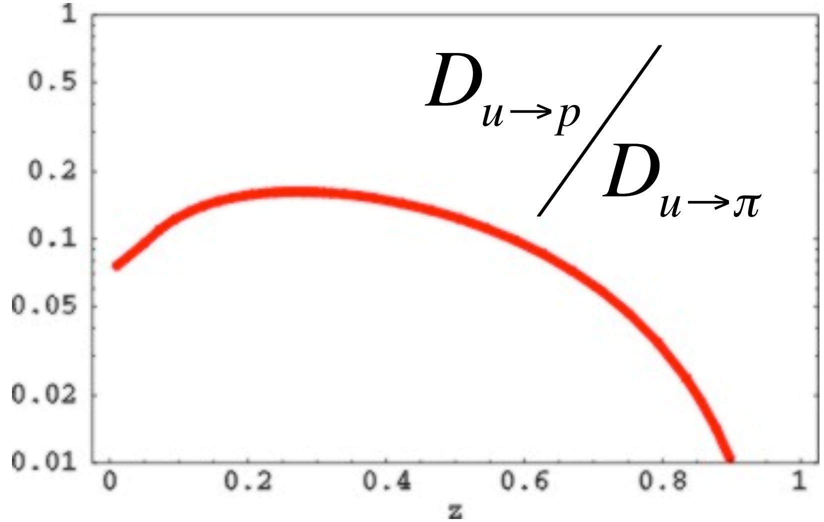
$$\Delta E \approx E \approx \alpha_s \hat{q} L_{therm}^2$$



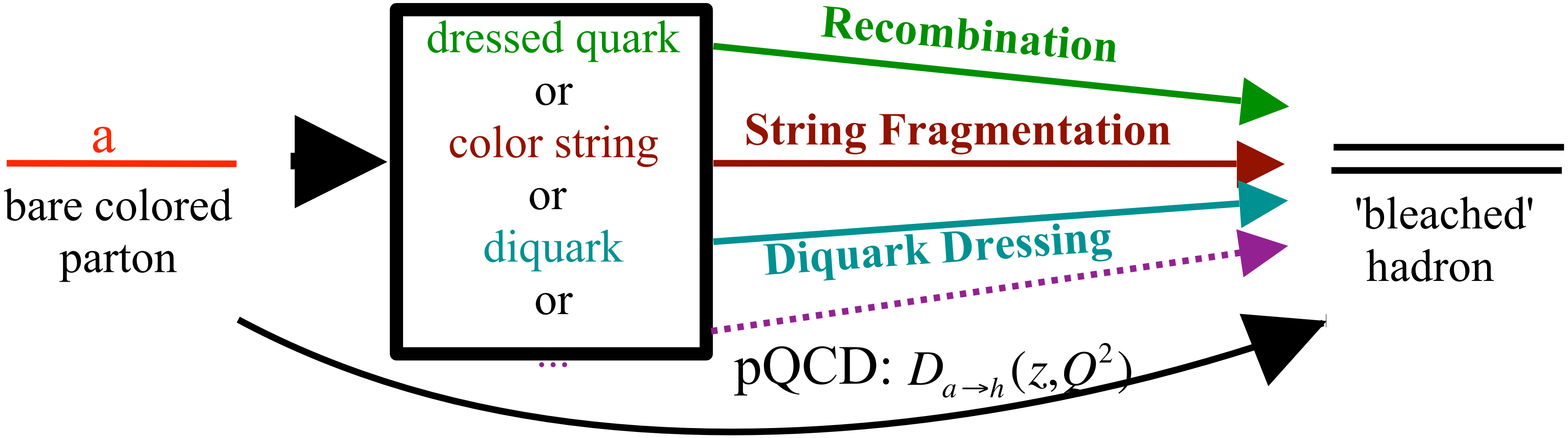
# Breakdown of independent fragmentation

- Parton e-loss does not affect $D_{u\to p}/D_{u\to\pi}$ in contrast to observation




- How does the bleaching of color charges proceed dynamically ?



# QCD Saturation Physics:
# QCD at the highest parton densities

Venugopalan McLerran; Jalilian-Marian,Kovner,Leonidov,Weigert; Balitsky; Kovchegov;…

At highest $\sqrt{s_{NN}}$, there is a qualitatively novel regime of QCD, in which

- Parton densities are maximal up to large scales $\boxed{\rho \sim 1/\alpha_s}$

$$Q^2 < Q^2_{sat} \sim (2-3\,GeV)^2$$

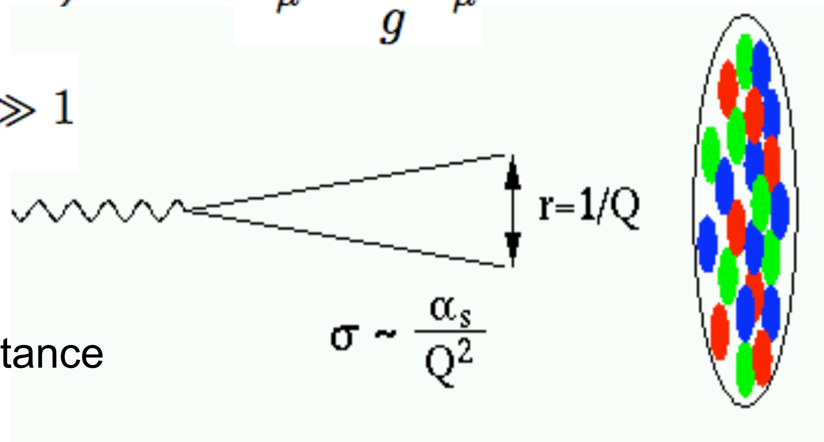
- Coupling constant is small $\boxed{\alpha_s(Q^2_{sat} \gg \Lambda_{QCD}) \ll 1}$

- Semi-classical methods apply

This requires that the action is large $(\hbar \longrightarrow 0)$

$$\tilde{A}_\mu = \frac{1}{g} A_\mu$$

$$\frac{S_{QCD}}{\hbar} \sim \frac{1}{g^2\hbar} \int d^4x \ \mathrm{tr}\ G^{\mu\nu}(x) G_{\mu\nu}(x) \gg 1$$



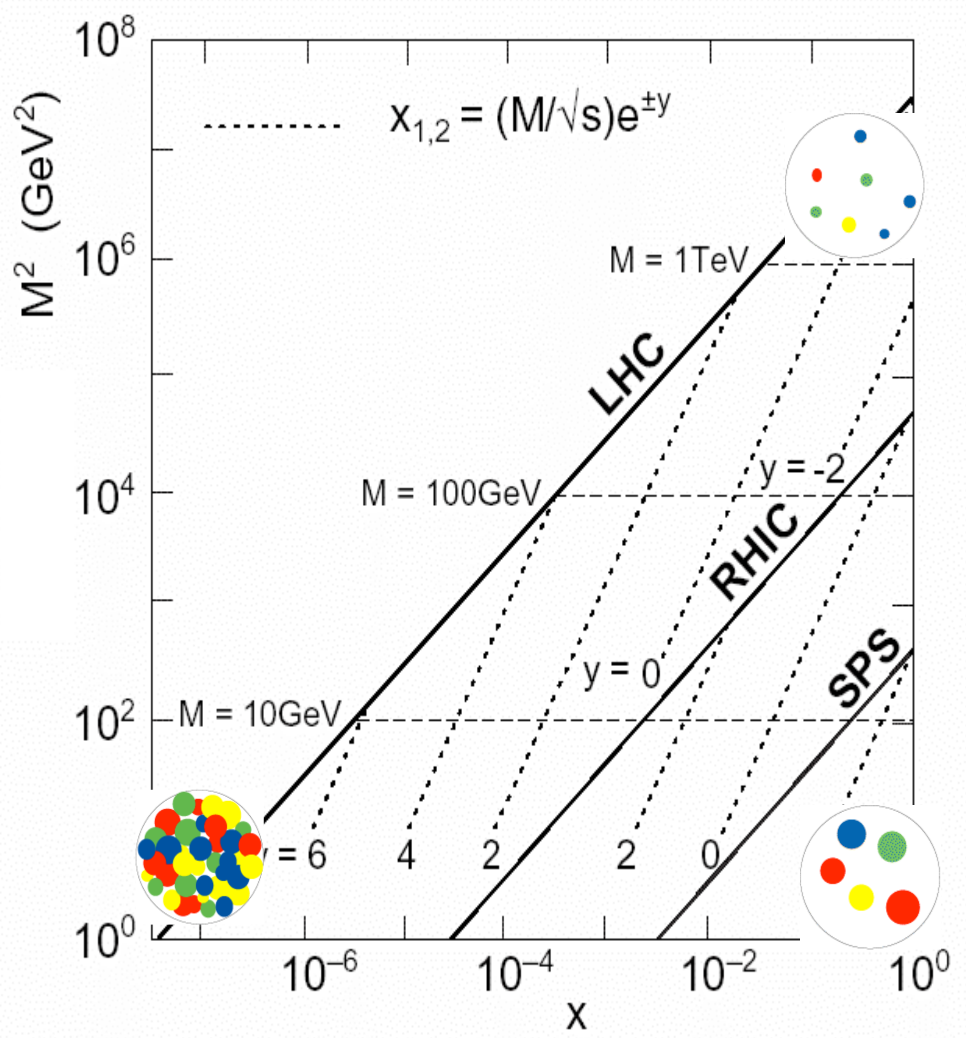

Need weak coupling and strong fields,
satisfied at sufficiently small Bjorken x,
where hard processes develop over long distance

Can we test this novel QCD regime in the laboratory?

# The kinematical range accessible

- Large $Q^2$
  - ⇨ abundant yield of hard probes
  - ⇨ precise tests of properties of produced matter
    - color field strength
    - collective flow
    - viscosity
    - …

- Small x
  - ⇨ higher initial parton density
  - ⇨ qualitatively different matter produced at LHC mid-rapidity?
  - ⇨ tests of saturation phenomena?
    - bulk observables
    - pt-spectra in scaling regime
    - rapidity vs. $\sqrt{s_{NN}}$ dependence
    - …



# The RHICness of Hard Probes

The probes:

- Jets
- identified hadron specta
- D-,B-mesons
- Quarkonia
- Photons
- Z-boson tags

The range:

$Q^2$ ,x, luminosity

The strategy:

Abundant yield

of hard probes

+ robust signal

(e.g. jet quenching

>> uncertainties)

= precision

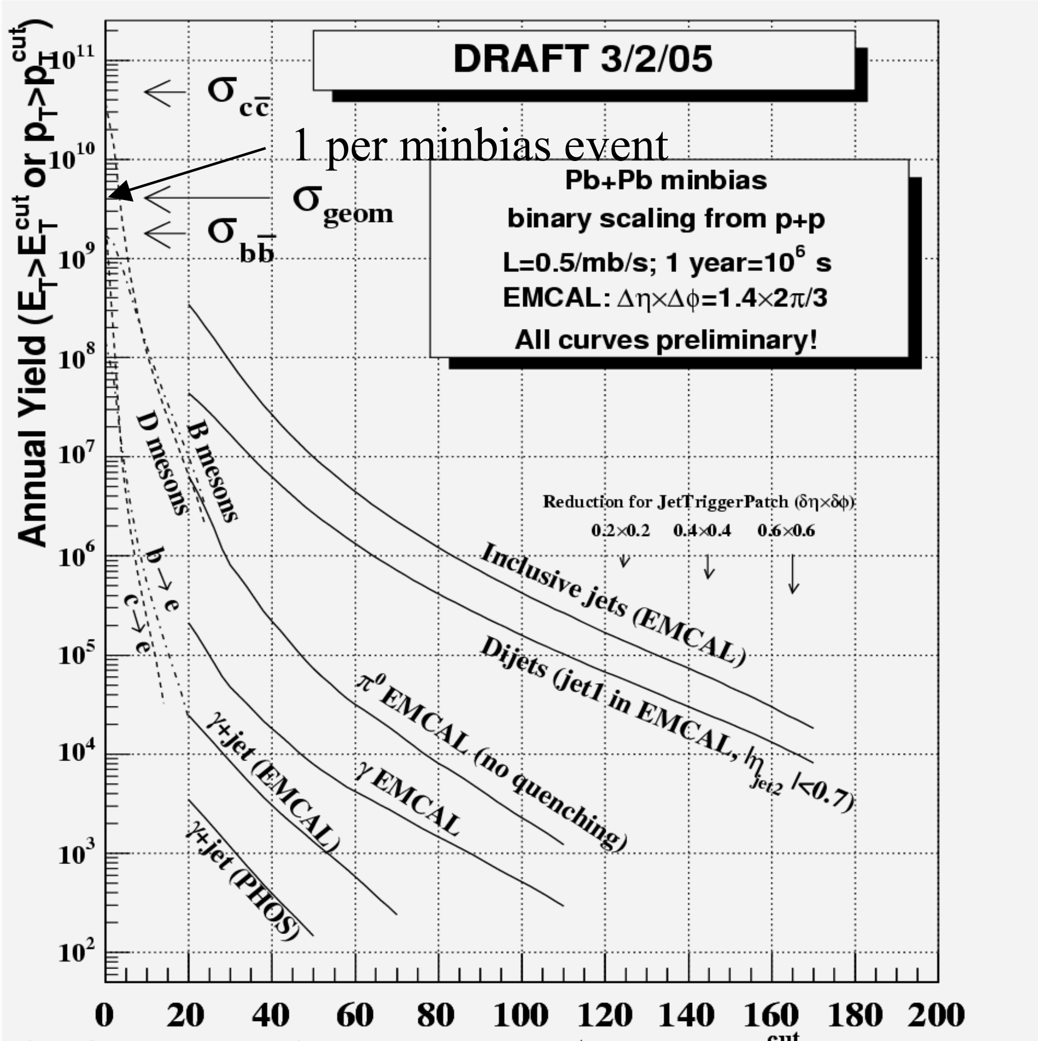



Fig. from P. Jacobs